

# Indoor Environments and Health: Moving Into the 21st Century

The quality of our indoor environments affects well-being and productivity, and risks for diverse diseases are increased by indoor air pollutants, surface contamination with toxins and microbes, and contact among people at home, at work, in transportation, and in many other public and private places.

We offer an overview of nearly a century of research directed at understanding indoor environments and health, consider current research needs, and set out policy matters that need to be addressed if we are to have the healthiest possible built environments. The policy context for built environments extends beyond health considerations to include energy use for air-conditioning, selection of materials for sustainability, and design for safety, security, and productivity. (*Am J Public Health*. 2003;93:1489–1493)

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## THE VERY PUBLICATION OF AN

issue of the *American Journal of Public Health* on “the built environment” signals a timely recognition of the relevance to health and well-being of the indoor environments where people spend most of their time. Even in temperate climates, including that of the United States, people spend most of their time indoors: at home, at work, in transportation, and in many other public and private places. The quality of these environments affects well-being and productivity, and risks for diverse diseases are increased by indoor air pollutants, surface contamination with toxins and microbes, and contact among people in these places. These are not new problems; they have been the focus of research and of control efforts for decades. The emphasis on the built environment indicates a shift toward a more holistic approach to indoor environments and the public’s health, a shift consistent with the broadening recognition of the

multiple levels of environmental factors, from the personal to the global, that determine an individual’s health.

Here we offer a perspective on this shifting emphasis that has led to a move from consideration of specific problems within indoor environments, such as radon and lung cancer, to a broader view that involves a greater emphasis on prevention. We recognize that some of the specific problems of indoor environments remain quite relevant and are a current focus for research, public concern, policy development, and even litigation. The health consequences of dampness and mold are a current example, and there are always emerging issues such as phthalates, organophosphates, and pyrethroid pesticides. Our intent is not to cover these individual topics, which have been reviewed in depth elsewhere.<sup>1</sup> Rather, we offer an overview of nearly a century of research directed at understanding indoor

environments and health, consider current research needs, and set out policy matters that need to be addressed if we are to have the healthiest possible built environments. We note that the policy context for built environments extends beyond health considerations to include energy use for air-conditioning, selection of materials for sustainability, and design for safety, security, and productivity.

## HISTORICAL PERSPECTIVE: PROBLEMS RECOGNIZED

Theories have long been advanced with regard to building ventilation and health. At the start of the last century, ventilation was viewed as healthy and as decreasing risks for infection.<sup>2</sup> The important early work of Constantin Yaglou, reported in the 1930s, established a paradigm for using ventilation as a means of achieving thermal and odor comfort in the built envi-

ronment.<sup>3,4</sup> For the next 50 years, dilution of human odors motivated the mechanical design of buildings and guided the use of often large heating, ventilating, and air-conditioning systems. In the latter part of the 20th century, as health and comfort problems associated with buildings became apparent, Ole Fanger and others pointed out that office equipment, materials, and even heating, ventilating, and air-conditioning systems themselves add to the odor and contaminant load of buildings and cause discomfort to occupants.<sup>5</sup>

In the 21st century, we have returned to concern for airborne spread of infection. With new analytical tools that can isolate specific strains of viruses from a room air sample or a specimen of nasal mucus, we can further advance our understanding of the role of ventilation and health and the potential for interrupting disease transmission in indoor environments. Perhaps the most dramatic demonstration of the need for new information on this issue was the dissemination of anthrax spores in postal facilities during the 2001 bioterrorism episode.

The more contemporary recognition of the relevance of the built environment to health came when measurements of levels of specific pollutants were first made in indoor air and the major contributions of indoor exposures to total personal exposures to air pollution were recognized. This recognition was broadened by such dramatic problems as mobile homes that could not be occupied because of extremely high levels of formaldehyde from building materials, the finding of homes with radon levels as high as those in underground uranium mines, and the appearance of a new clinical syndrome, often re-

ferred to as “sick-building syndrome,” that was linked to the building environment.

Some of the first measurements of indoor air pollutants were made in the 1960s.<sup>6</sup> In 1965, for example, Biersteker and colleagues<sup>7</sup> measured nitrogen dioxide levels in Dutch homes, finding that this outdoor air pollutant was present at high levels in homes with gas-fired combustion devices. Some of the initial measurements of tobacco smoke components were made in the 1970s,<sup>8,9</sup> and asbestos fibers were found in indoor air in public buildings and schools in the late 1970s and early 1980s.<sup>10</sup> Radon had been measured in indoor air as early as the 1950s but gained prominence as large numbers of measurements were taken in the 1970s and 1980s and homes were found with dramatically high concentrations. The problem of lead paint and lead-contaminated surface dust in inner-city homes was recognized in the 1950s and 1960s.<sup>11</sup>

The health- and risk-relevant concept of total personal exposure to pollutants was introduced in the 1970s and provided a framework for integrating and interpreting pollutant measurements taken indoors and outdoors.<sup>12</sup> In the microenvironmental model, total personal exposure to a contaminant is the time-weighted average of pollutant concentrations in the various “microenvironments” where time is spent. In the 1980s, investigators involved with the US Environmental Protection Agency’s Total Exposure Assessment Methodology Study used this model to comprehensively assess the contributions of indoor and outdoor exposures to total personal exposures to selected volatile organic chemicals, such

as benzene.<sup>13</sup> This study yielded the then startling conclusion that indoor pollution sources are generally a far more significant contributor to total personal exposures to toxic volatile organic compounds than are releases by some industrial sources into outdoor air. The Harvard Six-Cities Study, recognized as a landmark investigation of outdoor air pollution, also proved to be an invaluable research platform for understanding residential indoor air pollution and its strong contributions to total personal exposures to a number of pollutants, including particles, sulfates, and nitrogen oxides.<sup>14–16</sup>

## SOME PROBLEMS SOLVED

The measurement of these and other indoor air pollutants was quickly followed by research directed at their health effects. Epidemiological studies with cross-sectional and cohort designs focused on the risks of exposures at home, and a more limited number considered workplace exposures, particularly to tobacco smoke. Case-control studies and a few cohort studies of secondhand smoke exposure and lung cancer risks among nonsmokers were carried out. The risks of cancer associated with asbestos and radon were estimated through extrapolation of risks from studies of workers,<sup>10,17</sup> but ecological and case-control studies of indoor radon and lung cancer in the general population were also initiated as early as the late 1970s.<sup>18</sup>

Studies of infants and children addressed adverse respiratory effects of nitrogen dioxide, secondhand tobacco smoke exposure, and biological agents, particularly indoor allergens. The earliest of

these studies date to the late 1960s, and research conducted over the ensuing decades has provided convincing evidence for adverse effects of secondhand smoke, radon, and some biological agents. The evidence remains mixed in the case of certain other indoor pollutants, such as volatile organic compounds and nitrogen dioxide.

Research on the adverse effects of involuntary smoking on the respiratory health of children began in the late 1960s; the first studies on involuntary smoking and lung cancer were published in 1981.<sup>19,20</sup> The possibility of preventing exposure through elimination of indoor smoking was always clear, and as the epidemiological evidence mounted, increasing numbers of municipalities and states implemented policies designed to reduce or ban smoking in public places and workplaces. By 1986, the US surgeon general and the National Research Council had concluded that involuntary smoking causes lung cancer and has adverse effects on the respiratory health of children<sup>21,22</sup>; the list continues to expand, now including coronary heart disease as well.

With these causal conclusions, the debate over tobacco use shifted from the rights of an individual to use a product to the right of the public to breathe clean indoor air. Increasingly stringent control measures had broad effects; the majority of workplaces in the United States are now smoke-free, as are almost all commercial air flights, and levels of cotinine, the tobacco smoke biomarker, have declined sharply in the United States in recent years.<sup>23</sup> Reducing involuntary smoking in homes is a remaining challenge, one that can be addressed prima-

rily through education. Unfortunately, passive smoking remains a worldwide problem, particularly for women and children.<sup>24</sup>

Indoor radon, labeled “the colorless, odorless killer,” gained notoriety in the United States in the early 1980s, after media reports of a Pennsylvania home with such high levels that the nuclear power plant worker who lived there triggered the radiation monitoring system at the plant when he arrived at work. In the subsequent 20 years, we have gained an increasingly complete picture of the risks posed by indoor radon exposure.<sup>25</sup> A pooled analysis of data from 11 cohort studies of underground miners was carried out to estimate the risks of indoor radon, with complementary evidence gained from case-control studies of lung cancer in the general population.<sup>18,26</sup> Elegant experimental models, involving irradiation of single cells with single alpha particles, provide results consistent with a linear nonthreshold relationship between typical concentrations of indoor radon and lung cancer risk.<sup>27,28</sup> The source of most indoor radon, soil gas, is well characterized, and radon concentrations can be measured cheaply and with reasonable accuracy.

In spite of the abundant scientific evidence supporting strategies for radon control, including measuring and mitigating homes with high levels of radon and building radon-resistant homes, the voluntary initiatives of the Environmental Protection Agency have met with limited acceptance by the public.<sup>29–31</sup> According to agency reports, 18 million US homes have been tested and 50 000 homes mitigated since the mid-1980s.<sup>32</sup> The voluntary approach is strengthened in instances in

which radon testing is a standard requirement in purchase and sales agreements for homes.

Asbestos, another inhaled carcinogen, was widely used in the United States through the 1970s as an insulating material in public and commercial buildings; it has also been used to insulate piping in residences, and there is a potential for exposures in homes if the asbestos-containing material is friable. Concern about asbestos indoors first followed the recognition that insulating materials in many schools contained asbestos and some of the first measurements in schools indicated the possibility of unsafe levels in the air. Under the Asbestos Hazard Emergency Response Act,<sup>33</sup> school systems had the option of either removing the asbestos or maintaining it in place. Initially, asbestos-containing material was removed from many schools, at substantial expense; however, this approach was reevaluated as further measurements were obtained and options for managing asbestos-containing materials in commercial buildings were considered. A risk assessment carried out by the Health Effects Institute proved pivotal in pushing control toward in-place management.<sup>10</sup> Concerns about indoor asbestos may arise again after it becomes widely known that tremolite asbestos fibers are contained in Zonolite insulation, which is used in millions of homes, businesses, and schools.<sup>34</sup>

Nitrogen dioxide, one of the first pollutants measured indoors, can adversely affect lung function at high concentrations; thus, when it was found to be emitted by such ubiquitous appliances as gas stoves, epidemiological stud-

ies were initiated on its effects on the respiratory health of children and adults.<sup>35,36</sup> The findings of these studies have not provided consistent evidence for adverse effects of nitrogen dioxide, and levels in homes have declined as stoves with electronic ignitions have replaced older stoves with gas pilot lights and cooking patterns in the United States have moved toward increasing use of microwaves and less cooking in general. Some higher level exposures persist, however. Gas stoves are still used for supplemental heating, particularly among individuals who reside in public housing units, which are often not submetered for gas use. Also, quite high levels of nitrogen dioxide have been measured in poorly ventilated indoor ice rinks resurfaced with machines powered by gasoline or diesel engines.<sup>37</sup>

Biological agents have proved challenging; they are myriad and cause disease through both infectious and noninfectious mechanisms. Nonetheless, we have sufficient evidence to prevent the diseases caused by certain specific agents. Transmission of *Legionella* species through inadequately maintained cooling equipment for heating, ventilating, and air-conditioning systems and building water systems is well recognized, and building-related<sup>38</sup> (as well as cruise ship) epidemics of *Legionella* infection can be avoided through proper cleaning and maintenance. Numerous indoor allergens have been measured, and some have been linked to exacerbation and possibly causation of allergic diseases, including asthma. Control measures can reduce exposures to certain of these agents (e.g., cockroach and mite antigens), but substantial health benefits

have not been readily shown, in part because of the difficulties involved in maintaining reduced levels.<sup>39</sup>

## APPROACHING THE PROBLEMS REMAINING TO BE SOLVED

The single most pervasive and harmful indoor air problem worldwide is the oldest: smoke from fires. Domestic cooking and heating with biomass fuels of wood, crop residues, dried animal dung, or charcoal and coal can produce substantial indoor concentrations of particles, carbon monoxide, and polycyclic aromatic hydrocarbons. According to the World Health Organization's 2002 report<sup>40</sup> on global burden of disease, the almost daily exposure to smoke among billions of people, primarily women and young children, is the 8th leading cause of disability-adjusted life years lost, accounting for nearly 3% of the world's total burden of disease.

For more than 2 decades, we have known that improving stove efficiency, providing working flue vents, and improving fuel quality (e.g., switching from biomass fuels to propane or liquefied petroleum gas) could dramatically reduce acute respiratory infections, chronic lung and heart disease, and blindness. China has introduced stove improvement programs on a massive scale, and these programs have been successful. Land reclamation programs in India have demonstrated that investments in biogas digesters and liquefied natural gas cook stoves will be made as economic prosperity increases. However, the prospects for improvements among individuals trapped in third world poverty are dim, in that the costs of less

polluting cooking and heating fuels or stoves are prohibitive.

Many of the recognized indoor air quality problems facing developed countries are avoidable. If achieving a healthy indoor environment were a specific design criterion for buildings, many of the recurring problems of mold, pest allergens, radon, organic compounds, nitrogen dioxide, and carbon monoxide could be controlled. Indoor tobacco smoking has been reduced, but achieving effective control in homes remains a challenge; educational strategies are needed, particularly for protecting those at greatest risk, such as infants and children with asthma. Attention should be focused on particularly critical building environments; because children spend a substantial amount of their time in them, schools are one obvious example.

One lesson that has been learned repeatedly is the need to approach the built environment with multidisciplinary teams, whether the focus is on research, design and problem solving, or planning for the future. There is far too much isolation of the professionals involved—including public health and medical scientists and researchers, architects, engineers, city planners, and building managers—and there is insufficient engagement with the needs of the population itself.

We have convened interdisciplinary meetings to address indoor air quality issues and have been impressed with the immediate recognition among the participants of the necessity for interdisciplinary interactions on such issues as sick-building syndrome, air cleaning, and the level of optimal humidity.<sup>41,42</sup> Over the past several decades, the professional occupation category of indoor air

quality specialist has developed, and there are private firms providing indoor air quality services. Since 1978, the triennial indoor air conferences held by the International Academy of Indoor Air Sciences have offered an international venue for scientific exchange among the many disciplinary experts concerned with the built environment. Some of the critical topics have been addressed by committees of the National Research Council, the Institute of Medicine, and other organizations.<sup>18,43,44</sup>

With an ever-growing research base available, the scientific evidence on indoor air should inform the process of designing and maintaining buildings. All too often, well-intended inclusion of indoor air quality as a consideration is reduced to a simple checklist of general items to be avoided and to compliance with ventilation codes. This approach reflects a “dumbing down” of the complex ways in which humans interact with the environment. A more comprehensive rethinking is needed on the physiological, sociological, ergonomic, and psychological characteristics of the built environment that affect health and well-being.

Many building codes and design criteria are not soundly based in regard to their consequences for human performance (e.g., lighting requirements). Ventilation requirements for buildings have been assessed, along with those for temperature and humidity, more on the basis of meeting comfort criteria than with an orientation toward health or even productivity. Remarkably, there has never been a comprehensive study on the role of ventilation and health and comfort in homes. The current guidelines of the American Soci-

ety of Heating, Refrigerating, and Air Conditioning Engineers<sup>45</sup> recommend a minimum air exchange rate of 35% per hour for homes. However, associations of homebuilders have resisted attempts to specify mechanical means to achieve this recommended exchange rate or to institute higher exchange rates for homes.

New issues related to the built environment will inevitably emerge. On the current short list of chemicals likely to be of concern are several synthetic organic compounds: polychlorinated biphenyls in building materials; phthalates in polyvinyl chloride materials used in flooring, wall coverings, cables, foam, and other products of which plastic is a component; polybrominated diphenyl esters, which are fire retardants used in many products, including computers; pesticide residues, including the recently introduced family of pyrethroids; and cleaning agents such as those with phenol, among other potentially sensitizing compounds.

The current concern about intentionally introduced viruses and other infectious organisms as acts of bioterrorism will advance research on the role of building ventilation and air cleaning in the transmission of pathogenic organisms. As more multidisciplinary research on health and buildings is carried out, the effects of space characteristics, materials, lighting, and air quality on stress and performance should become better understood. Studies of workforce health complaints related to building environments have been methodologically complicated by the nonspecificity of most complaints, and it is often impossible to separate causal effects of engineering and design factors from

job stress, personal stress, and the perception of unsatisfactory indoor environmental conditions. A recently published research agenda for indoor environments and worker health emphasized building-related asthma and allergic diseases in addition to communicable respiratory infections and nonspecific building-related symptoms.<sup>46</sup>

Research continues, but in the case of some problems the public, Congress, and lawyers will not await more certainty from scientific investigations. For example, state and federal legislation on toxic mold has been proposed. Many individuals, building owners, and insurance companies have been affected by the consequences of water damage and molds, and there is uncertainty as to health risks and control approaches. Effective policy approaches are urgently needed for the problem of indoor molds and moisture. The current situation is reminiscent of the past tumultuous debates and litigation around asbestos in buildings. In the 1980s and early 1990s, expensive removal of asbestos-containing material was the first course of action regardless of whether the presence of that material actually exposed occupants to asbestos fibers. Currently, insurance companies are attempting to write policies excluding mold liability or simply refusing to provide coverage in states where mold claims are widespread. This situation needs resolution through science-based policies and perhaps legislation, but the needed research has yet to be carried out.

We are hopeful that this issue of the *Journal* will contribute to the continuing development of the research and policy agenda for improving the



built environment. Unfortunately, this topic has received inadequate emphasis, particularly in comparison with the substantial resources directed toward outdoor air pollution. ■

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This article was accepted April 20, 2003.

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